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A Summary of Analysis and Test Support for the Munitions Survivability Technology Program

by John Starkenberg, John D. Sullivan, Warren W. Hillstrom,
Richard E. Lottero, Wai K. Chin, and Thomas J. Mulkern

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Abstract

The Munitions Survivability Technology (MST) program was initiated by the U.S. Army Defense Ammunition Logistics Activity to develop a rapidly deployable system of fragment barricades combined with lightweight fire-inhibiting blankets, with guidelines for their use to prevent or reduce propagation of explosions and fire between stacks of Army munitions. In order to ensure the maximum effectiveness of such systems, the U.S. Army Research Laboratory undertook a program to elucidate relevant propagation mechanisms, enhance predictive techniques for propagation, and develop data required for the evaluation of the system to be fielded. Available resources included the FRAGPROP model for predicting propagation of detonation and burning reactions between ammunition stacks, the FRAGGEN model for predicting fragmentation of items that are not characterized in arena tests, existing data on gun propellant and rocket motor vulnerability to fragment attack, analyses and test procedures developed in conjunction with the Navy's High-Performance Magazine program, and data from hazard classification tests. The MST program was divided into three broad areas: (1) fragment propagation, (2) crushing propagation, and (3) fire propagation. Tests, simulations, and analyses were conducted in each of these areas. The program culminated in two large-scale demonstration tests.

Acknowledgments

Duane Scarborough and Robert Rossi of the U.S. Army Defense Ammunition Logistics Activity sponsored this program. Many individuals contributed to its successes. The fragment propagation, arena, firebrand characterization, and final demonstration tests were conducted by Jackie Brown, Carl Halsey, and their crew at the Naval Air Warfare Center, China Lake, CA. Charles Pergantis of the U.S. Army Research Laboratory (ARL), Aberdeen Proving Ground, MD performed IR videography of the firebrand tests. Dr. Lawrence Vande Kieft of ARL assessed the ignitability of wood by hot fragments. The water penetration experiments were performed by Vincent M. Boyle, Alfred Bines, Oliver Blake, William Sunderland, Anthony Canami, and Steven Stegall, all of ARL. The Concertainer test was arranged by Raymond Cregar of ARL and performed by John Miller and his crew from the Aberdeen Test Center, Aberdeen Proving Ground, MD. Munition crushing computations were performed by Patsy Simmers of ARL. Gould Gibbons, Thomas Adkins, Dawnn Saunders, Alfred Bines, and William Sunderland, all of ARL, worked on the ballistic testing of blankets. Dr. Archibald Tewarson and Dr. Peter Wu, both of Factory Mutual Research Corporation, contributed to the laboratory-scale blanket heat penetration tests. Dr. John Vanderhoff and Dr. Richard Beyer, both of ARL, aided in laboratory-scale propellant and flame testing of blankets. The advice and guidance of Dr. Robert Frey of ARL throughout this program were invaluable.

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1. Background

When ammunition is stored in the open, as in contingency operations or when awaiting transportation (e.g., in ports as shown in Figure 1), it is vulnerable to hostile attack or accidental stimuli that may produce fires, violent explosions, propagation between stacks, and consequent large-scale losses and damage. Mechanisms of reaction propagation vary widely, depending on the accident scenario and the munitions involved. An informal review of ammunition accident history (Starkenberg et al. 1996) revealed that the most common mechanism of propagation of reaction between ammunition stacks involves ignition of fires by fragments, debris, or firebrands from the source explosion and subsequent violent reaction of munitions in those fires. Such an accident occurred in Doha, Kuwait in 1991. Its aftermath is illustrated in Figure 2. Prompt propagation via primary fragments also remains important. Where barricades are used to prevent this, crushing propagation involving the barricade becomes a possibility.

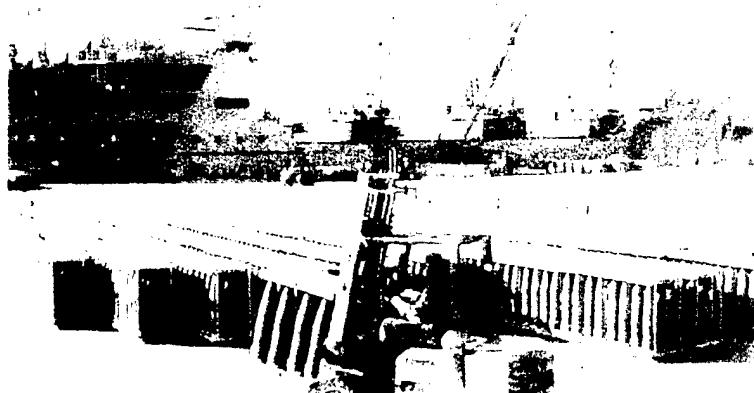


Figure 1. Army ammunition awaiting transportation in port.

The Munitions Survivability Technology (MST) program was initiated by the U.S. Army Defense Ammunition Logistics Activity, Picatinny Arsenal, NJ. Its objective was to develop a rapidly deployable system of fragment barricades combined with lightweight fire-inhibiting blankets, with guidelines for their use to prevent or reduce propagation of explosions and fire between stacks of Army ammunition. In order to ensure the maximum effectiveness of such systems, the U.S. Army Research Laboratory (ARL) undertook a program to elucidate relevant propagation mechanisms, enhance predictive techniques for propagation, and develop data required for the evaluation of the system to be fielded.



Figure 2. Aftermath of the ammunition accident at Doha, Kuwait.

The primary candidate barricade for this program was a system produced by Federal Fabrics-Fibers, Inc. (FFF) of North Chelmsford, MA. It consists of stacked tubular bags constructed of seamless woven Kevlar with an inner polymer bladder holding water. This product is hereinafter referred to as the FFF barricade. During the course of the program, the manufacturer provided bags in increasing diameters (ranging from 18 to 54 in), requiring decreasing numbers of bags to construct a barricade. The 36-in diameter version of this system is shown in Figure 3. Because of concerns regarding the survivability of this barricade in a long-term cookoff scenario (even when the water is gelled to prevent rapid leakage after bag penetration), an alternative barricade built from a commercially available system (Hesco-Bastion Concertainer) was also tested. No predetermined blanket was specified. Rather, the blanket was designed as part of this program.

2. Technical Issues

A number of technical issues required resolution. Models to predict prompt propagation of detonation between stacks via fragmentation had been developed, but they required validation and, possibly, improvement. Fragment barricades must withstand successive explosions associated with long-term cookoff of ammunition in fires. Further, barricades may promote propagation by crushing nearby acceptor stacks. The nature of burning debris ejected from an ammunition fire and the way in which it is distributed was not well understood, and the response of ammunition stacks to burning debris had not been determined. Blankets may intensify fires if they are penetrated by burning debris that ignites the stacks they protect. Thus, they must provide at least some level of ballistic protection.

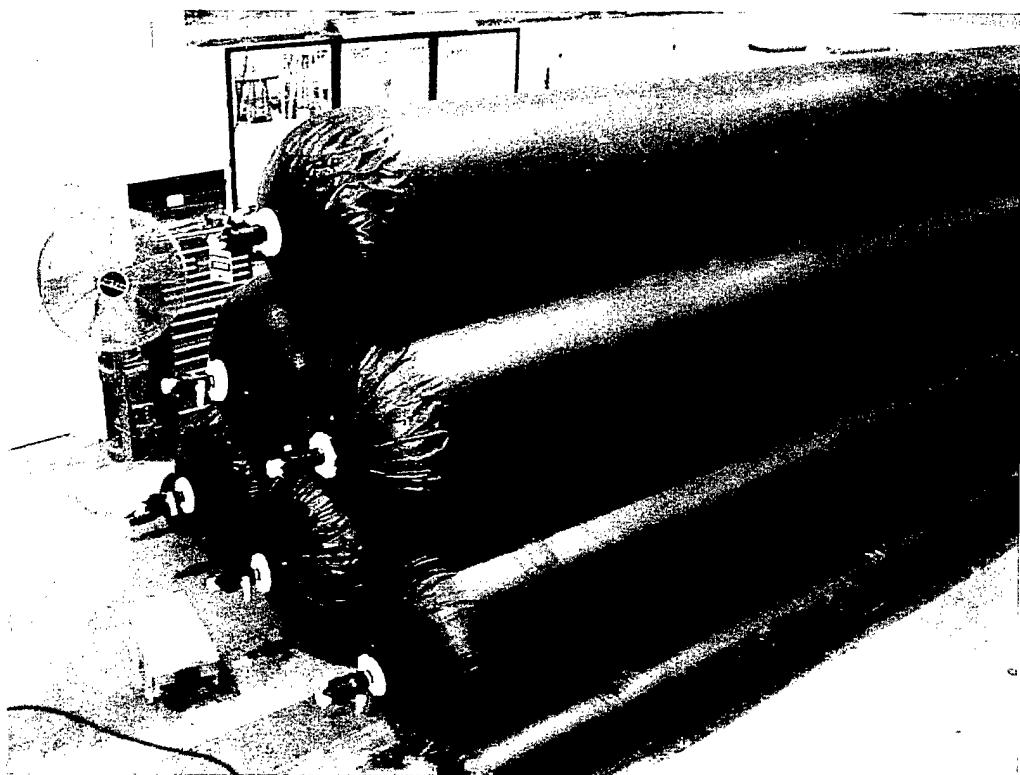


Figure 3. Water-filled barricade system with six 36-in tubes.

3. Resources

Available resources include the FRAGPROP model for predicting propagation of detonation and burning reactions between ammunition stacks, the FRAGGEN model for predicting fragmentation of items which are not characterized in arena tests, existing data on gun propellant and rocket motor vulnerability to fragment attack, analyses and test procedures developed in conjunction with the Navy's High-Performance Magazine program, and data from hazard classification tests.

FRAGPROP (Starkenberg et al. 1996) is based on an earlier computer program called FRAGHAZ (McClesky 1988) that was developed to predict the hazard to a human target due to fragmentation from an exploding ammunition stack. FRAGPROP is designed to predict detonation and burning propagation probabilities between two ammunition stacks as functions of the distance between them. The donor stack description and Monte-Carlo analysis of the trajectories of the fragments characterizing that stack are nearly identical to those used in FRAGHAZ. Effects of penetrating external containers and user-specified limits on fragment mass and

initial elevation angle were added. FRAGPROP includes descriptions of the vulnerable components (warheads and rocket motors) of munitions in the acceptor stack and applies detonation initiation and burning ignition criteria whenever a fragment impacts the target stack. The effects of penetrating an external container are also included here. The vulnerability of a weapon component to initiation of detonation by fragment impact is described by the Jacobs-Roslund formula for critical impact velocity (Liddiard and Roslund 1993). The model for ignition of burning makes use of a threshold corresponding to a specified residual velocity computed using the THOR equations. In general, the residual velocity appropriate for use with a specific ammunition item is not known, and a residual velocity of zero has been used as a worst case in prior analyses. The burning produced may be either mild or violent. The violence of the burning response is not predicted by FRAGPROP. Typical FRAGPROP predictions are shown in Figure 4.

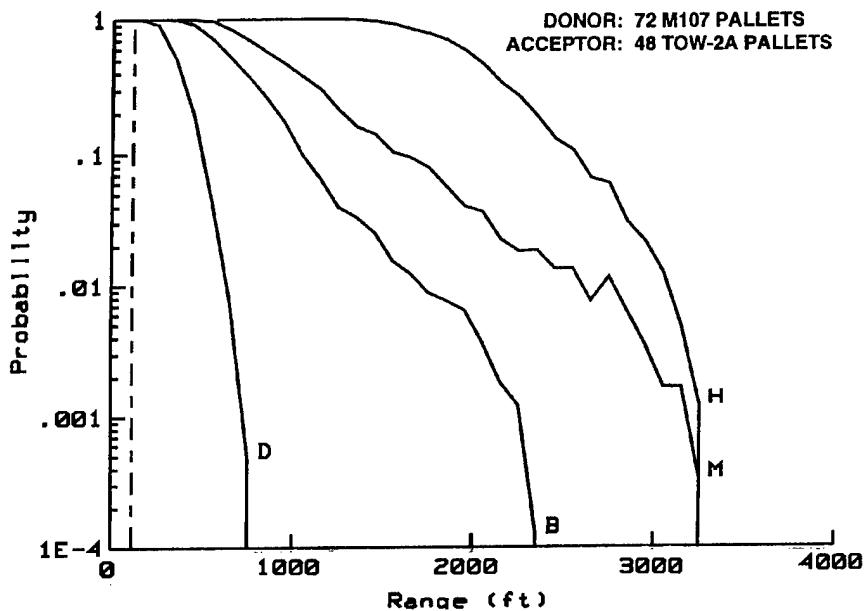


Figure 4. Typical FRAGPROP predictions for propagation of detonation (D) and burning (B) from a donor stack of M107 projectiles to an acceptor stack of TOW-2A missiles.

FRAGGEN (Starkenberg et al. 1996) is a simple model for estimating the fragment output from any item that can be represented as a cylindrical charge with a fragmenting case. It does not account for fragment interactions with neighboring items. The distribution of fragment masses is given as a function of the average fragment mass by the Mott equation (Victor 1994). The average fragment mass may be related to the properties of the charge and casing, and the total fragment mass is

equated to the casing mass. The velocity of the fragments is determined using the Gurney analysis for the assumed configuration and is the same for all fragments.

An early study of the vulnerability of cased gun propellant to fragment attack was conducted by the New Mexico Institute of Mining and Technology (Collis et al. 1972) for the U.S. Army Ballistic Research Laboratories (BRL). This study includes tests in which cylindrical steel fragments with known characteristics were fired at various velocities at simulated U.S. 40-mm (brass casings) and 105-mm (brass and steel casings) artillery ammunition containing either M1 (single-based), M2 (double-based), or M30 (triple-based) granular propellant. Some tests were also conducted on U.S. 5-in and Soviet 122-mm rocket motors. The parameters studied include fragment velocity, mass, temperature, and obliquity, as well as case material and propellant chemistry and geometry. Because of the instability of the fragments in flight and poor control of the impact obliquity (even though the impact faces of the cartridge cases were flattened), large regions of mixed results were obtained in this study and V_{50} values were reported. The threshold residual velocities corresponding to the V_{50} values vary between approximately 450 and 1,000 m/s. Results of an Air Force study of the mechanisms by which impacting fragments ignite cased granular gun propellants were reported by Gilman (ca. 1978). In order to facilitate fragment firing and accurately control impact conditions, fragment-simulating projectiles (spheres, cubes, and, occasionally, cylinders) were fired against flat-plate-faced replica cartridge-case targets containing M1 (single-based) or M26 (double-based) propellant. In each series of firings, the impact velocity of the fragments was varied in order to accurately determine a threshold value. This approach greatly reduces or eliminates regions of mixed results so that V_{50} values need not be used. In this study, the residual velocities varied between 200 and 800 m/s. These values are lower than those determined in the BRL study. The highest values found in the Air Force study were generally associated with special target cover materials that are not representative of munitions (e.g., epoxyboard). Analysis of over 4,000 firings indicates that energy transfer from casing material heated by thermoplastic shear during the perforation process is the dominant mechanism causing propellant ignition. It is clear from a study of these data that residual velocity is not a sufficient criterion for predicting ignition of gun and rocket propellants. However, it is useful because casing perforation is prerequisite to ignition.

In conjunction with the development of the Navy's High-Performance Magazine, Tancreto et al. (1994) identified criteria for the propagation of reaction that is facilitated by intervening barricades in ammunition storage arrangements. The most important propagation mechanisms they identified are direct shock loading and crushing of the casing caused by impact of the barricade on acceptor ammunition. Their criterion for shock initiation is based on the concept of critical energy fluence. While this is not a directly measurable quantity, it can be computed

for a specific arrangement, and the presence or absence of propagation can be verified in experiments. The crushing-propagation criterion is related to the total deformation experienced by the acceptor, usually expressed as the ratio of the net change in a munition's diameter to its original diameter.

4. MST Program Structure

The Army ammunition inventory is vast, and the resources of the MST program were limited, precluding in-depth exploration of all technical issues. The tasks to be performed had to be carefully considered in light of prior work. Representative ammunition items were selected from the Army inventory, subject to availability. The MST program was divided into three broad areas: (1) fragment propagation, (2) crushing propagation, and (3) fire propagation. Tests, simulations, and analyses were conducted in each of these areas. The program culminated in two large-scale demonstration tests.

5. Fragment Propagation

5.1 Propagation Model Validation

In order to benchmark predictions from FRAGPROP, propagation tests using 155-mm M107 projectiles were conducted at the Naval Air Warfare Center (NAWC) at China Lake, CA (Hillstrom and Starkenberg 1998a, Starkenberg and Hillstrom 2000). The test arrangement is shown in Figure 5. The donor stands at the center and barriers are used to prevent interactions between acceptors. As shown in Table 1, the predicted frequencies of detonation and burning propagation are somewhat greater than those observed in the tests. While the results do not provide sufficient data to validate the FRAGPROP predictions with a high level of confidence, they indicate that they are reasonable representations of the actual responses of these munitions.



Figure 5. Arrangement for M107 propagation tests.

Table 1. Comparison of FRAGPROP predictions with benchmark test results at 28 ft.

Reaction Type	Predicted	Benchmark
Burning	80.0%	60.0%
Detonation	75.0%	37.5%

5.2 Burning Propagation

In addition, efforts were made to analyze existing data to establish models for ignition of burning reactions in energetic components caused by fragment impact (Frey and Starkenberg 1999). The data show that heating of casing material is the principal ignition mechanism. Thus, casing penetration is a minimum requirement for ignition. For thin casings, penetration with significant residual velocity may be required to produce temperatures hot enough to ignite propellant. However, analysis with FRAGPROP has shown that using a residual velocity of zero as a worst case criterion for ignition does not inordinately increase the distance associated with a given propagation probability over that predicted using higher residual velocities.

5.3 Fragment Model Validation

Arena tests, as shown in Figure 6, were conducted at NAWC to benchmark FRAGGEN predictions of fragmentation (Hillstrom and Starkenberg 1998a). In addition to layered Celotex panels for the collection of fragments, witness panels containing propellant canisters were present. For simplicity, an arena test on a single Hellfire missile was performed first. Aluminum fragments in addition to those produced by the warhead were recovered and analyzed as shown in Figure 7. The analysis indicates that the predicted mass distribution is accurate for the smallest fragments, which comprise most of the total number. Measured fragment velocities were much lower than the Gurney predictions employed by FRAGGEN, and the fragments failed to ignite any of the witness propellant canisters. Because the configuration used in the single Hellfire test does not represent the actual storage arrangement and in order to determine the effects of multiple simultaneous detonations and the presence of external packaging, an arena test on two Hellfire missiles in their containers was conducted. Comparison of the fragment mass distributions produced in the two tests indicates depopulation of the smaller fragment sizes in the second test. This renders the FRAGGEN predictions inaccurate. The fragments produced in this test started burning reactions in the witness propellant canisters. A final arena test with two 155-mm M864 ICM projectiles containing submunitions, conducted in an attempt to develop fragmentation data for this configuration, was not successful.

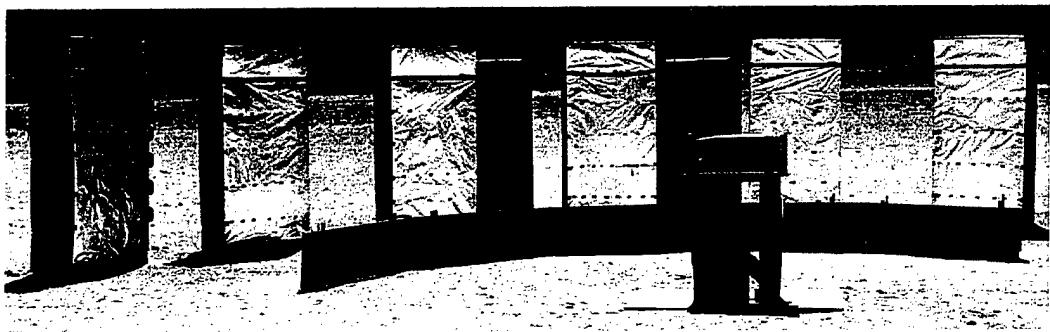


Figure 6. Arena test arrangement.

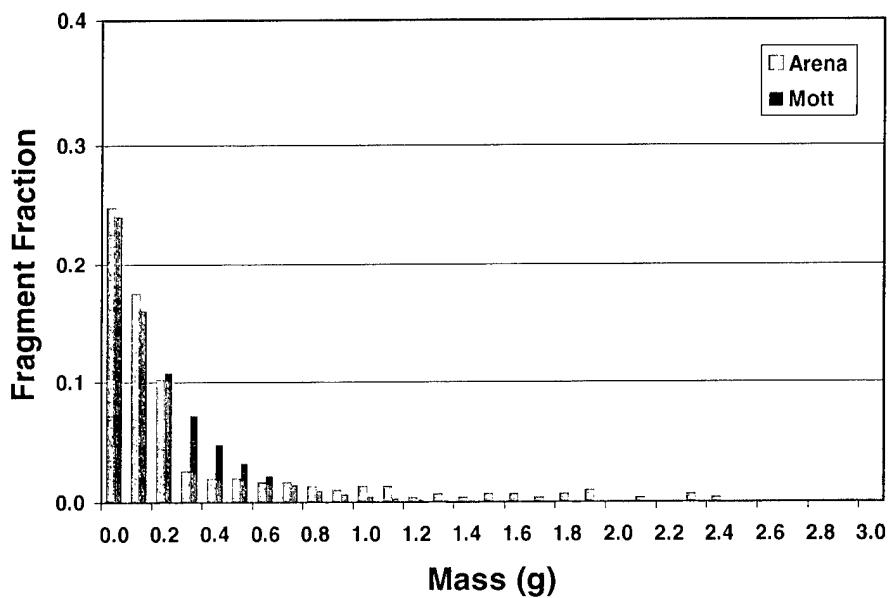


Figure 7. Comparison of the measured fragment mass distribution for a single Hellfire missile with FRAGGEN (Mott) predictions.

5.4 Water Penetration

In order to evaluate the effectiveness of water barricades against multiple fragments, water penetration experiments were conducted. The description and results of these tests have not been published elsewhere, so they are discussed in some detail here. M107 155-mm projectiles filled with Composition B were detonated singly and simultaneously in pairs with rotating bands in contact. The test arrangement for a pair of M107s and 3 ft of water is illustrated in Figure 8. The fragments (from the interaction zone in the case of pairs) were allowed to pass through screening apertures in armor shields and 0–3 ft of water on either side. The apertures allowed

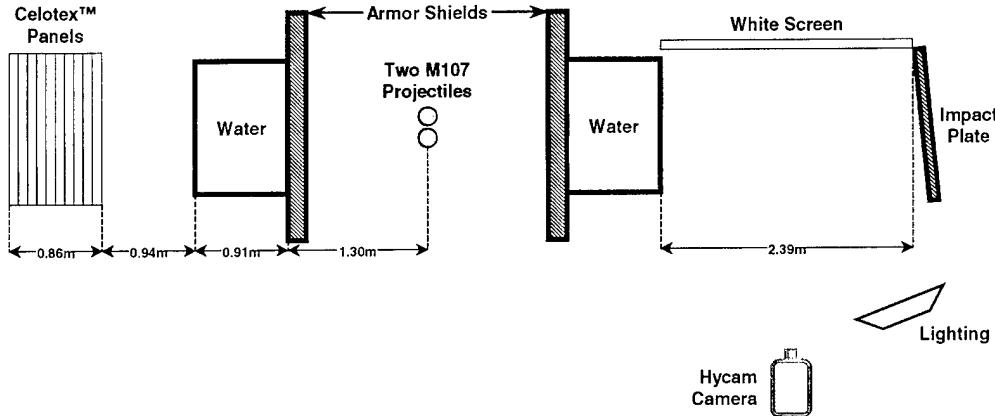


Figure 8. Water penetration test arrangement.

fragments from the polar zone from 79° to 108° to pass with an azimuthal width of 17.8° . On one side, the residual velocities of selected fragments were measured using a high-speed camera, and the penetrating fragments were collected on the other side.

The results of the five tests conducted are summarized in Table 2. The total mass of fragments collected from a single M107 was found to be consistent with published data. For M107 pairs, we compared our results to the data provided with the FRAGHAZ software. This data was collected from multiple projectiles and covers a larger range of polar angles. The most massive fragments and average fragment masses in our tests were considerably smaller than those found in the FRAGHAZ data set. Our fragment velocity data is sparse. Generally, we observed a slug of water accelerated as the fragments passed through, and its velocity as it emerged was also measured using the film record. The water slug punched a hole in the Celotex panels.

Table 2. Results of water penetration tests.

No. of M107s	Barrier		Recovered Fragments			Measured Velocities (m/s)			
	Material	Thickness (m)	Quantity	Mass (g)			Fragments	Water	Relative
				Heaviest	Total	Average			
1	Air	0.3048	94	196.3	1,299	13.8	1255	—	—
1	Water	0.3048	118	48.2	1,022	8.7	608	—	295
2	Water	0.3048	192	299.8	2,892	15.1	1159	1331	517
2	Water	0.6096	277	144.1	4,061	14.7	no camera record		
2	Water	0.9144	124	200.0	3,380	27.3	327	—	327
								0	—

With a single M107 and no water, a fragment with a velocity of 1255 m/s was observed. With 1 ft of water present, a fragment with a velocity of 608 m/s was observed. However, no meaningful comparison of these values can be made because the other characteristics of these fragments are unknown. To obtain a comparison that could be used to evaluate our results, an analysis of the FragHaz data was conducted. The velocity decay for penetration of an average fragment in each polar zone was predicted using the well-known fluid drag equation with a representative drag coefficient (0.85):

$$V_p = V_o e^{-kx_p},$$

where

$$k = \frac{\rho_L A_F c_D}{2m_F}.$$

Here, ρ_L is the fluid density, A_F is the presented area of the fragment, c_D is its drag coefficient, and m_F is its mass. V_o is the initial fragment velocity and V_p is its velocity after penetrating a distance x_p through the fluid.

The residual velocities determined in this manner can be compared to the measured fragment velocity relative to the measured bulk water velocity. The computed residual velocities for penetration distances of 1, 2, and 3 ft are plotted as functions of polar angle along with our measurements in Figure 9. A logarithmic vertical scale is used. The measurements for each of three fragments are represented by error bars extending from the relative velocity to the absolute velocity. They can be identified by reference to their colors and to the table. After 1 ft of penetration, our measured velocities were always considerably higher than the computed velocities, even when corrected for the bulk water velocity. After 3 ft of penetration in our tests, the fragments were stopped relative to the water. This can be compared to low computed velocities.

Because of the bulk acceleration of the water in the presence of blast and multiple fragments, it is less effective in stopping fragments than an analysis based on the penetration of single fragments without blast would suggest.

5.5 Cookoff Simulation

Because of concerns regarding the survivability of a water-filled barricade, tests simulating response of such barricades to long-term cookoff were conducted at the U.S. Army Research Laboratory at Aberdeen Proving Ground, MD (Sullivan 2001). The tests were conducted using gelled water in FFF barricades with six 36-in and three 54-in diameter tubes. Randomly oriented M1 105-mm projectiles filled with Composition B were detonated 10 ft from the base of the barricade at intervals

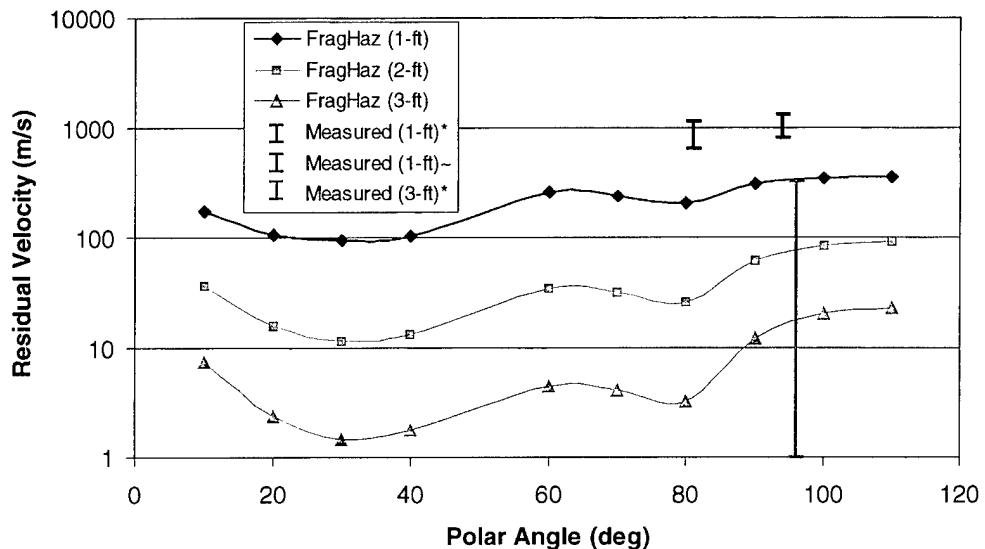


Figure 9. Comparison of residual velocities computed from FRAGHAZ data with those measured in water penetration tests.

approximating observed cookoff for this item. The initiation of up to 10 projectiles in each test was planned. Plywood witnesses were placed behind the barricades and examined between the firings.

The test arrangement and results for the 36-in diameter tubes are illustrated in Figure 10. Projectiles were detonated at approximately 3.5-min intervals. Even with the gelling agent present, the bags leaked and deflated before all the projectiles could be detonated. After four projectiles had been initiated, the firing position was too flooded with gelled water to continue.

The test arrangement and results for the 54-in diameter tubes are illustrated in Figure 11. Nine projectiles were detonated against these tubes at approximately 5-min intervals. After the second projectile was detonated, the front tube deflated sufficiently to allow the top tube to roll off the barricade.

No fragments were found to strike the witness in either test (although the first test was terminated prematurely and subsequent firings would have left the witness unprotected). Eventually, the protection afforded by the barricade is significantly diminished. The flow of gelled water over the firing area might have been sufficient to extinguish a fire.

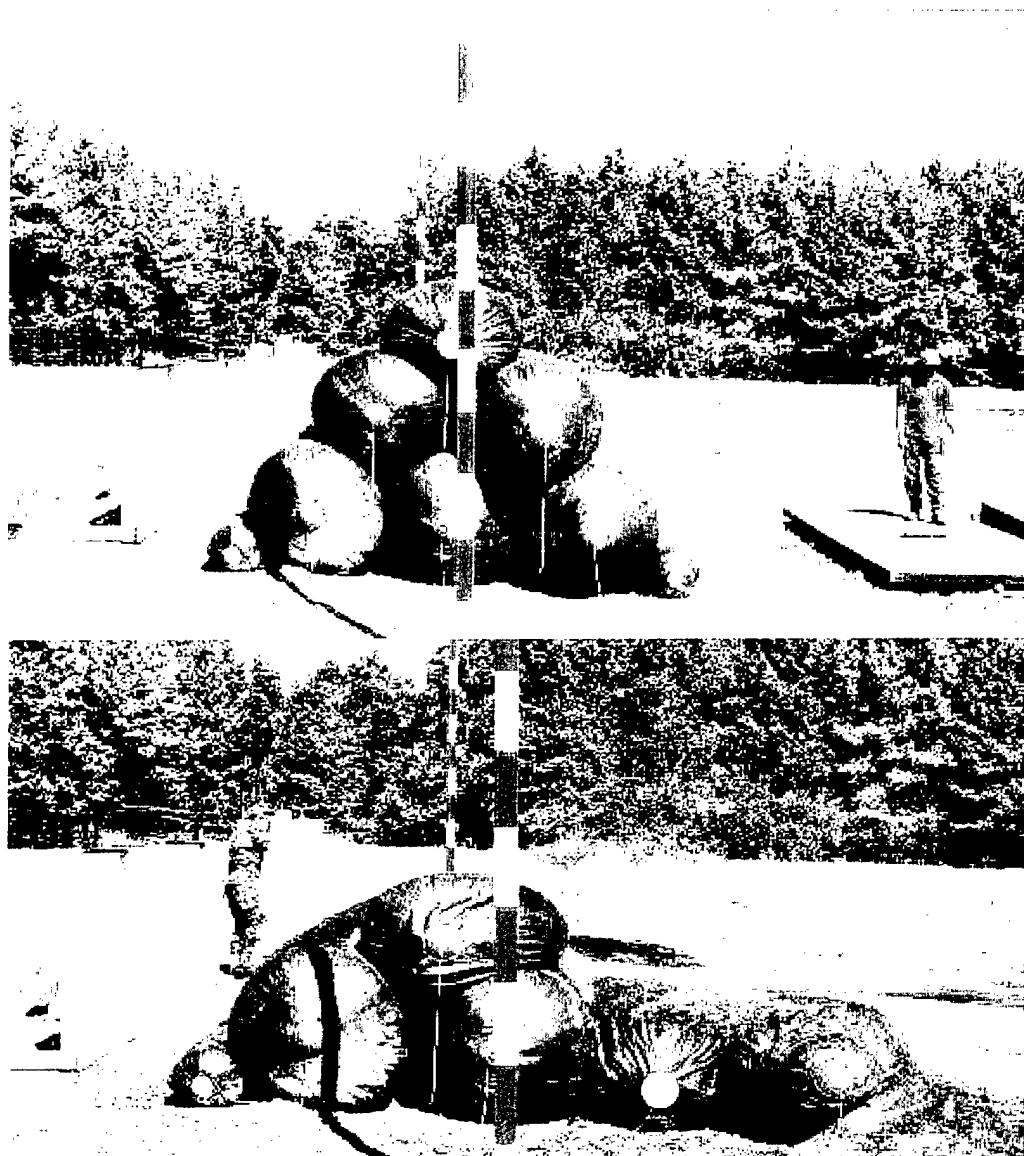


Figure 10. Arrangement and aftermath of simulated cookoff test with 36-in tubes.

5.6 Sand Barricade

As an alternative to the FFF water-filled system, a barricade constructed from Hesco-Bastion Concertainer was introduced into the program. This product consists of a series of linked, geotextile-lined, wire-mesh bins. The bins may be earth filled, and the barricade is not expected to exhibit survivability problems.



Figure 11. Arrangement and aftermath of simulated cookoff test with 54-in tubes.

In order to demonstrate its effectiveness against fragments, two Concertainer bins (shown in Figure 12) were filled with sand and tested at the Aberdeen Test Center at Aberdeen Proving Ground, MD against a simultaneously detonated pallet of M107 155-mm projectiles filled with Composition B. This test and its results have not been previously reported. The test arrangement is shown in Figure 13. The M107 pallet (shown in Figure 14) was placed 10 ft from the front of the sand barricade, which

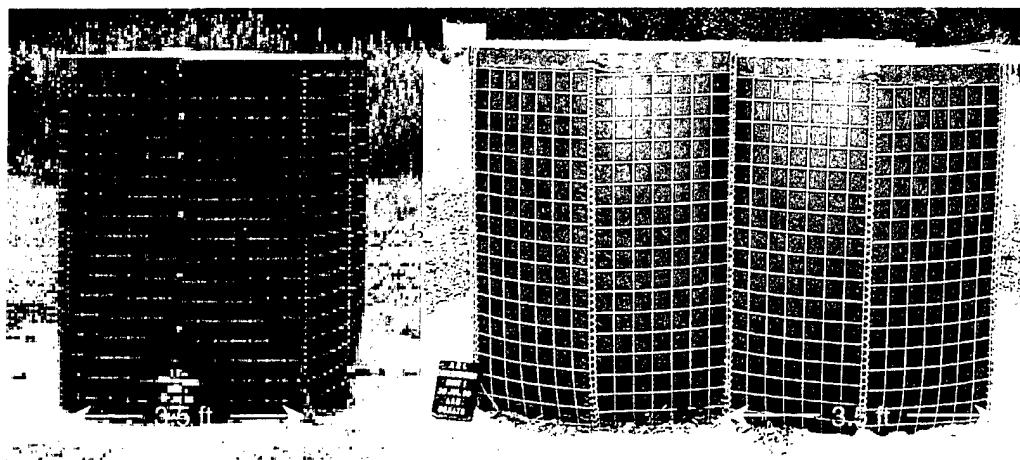


Figure 12. Concertainer barricade, as tested.



Figure 13. Test arrangement for Concertainer barricade.



Figure 14. M107 donor pallet.

was approximately 3.5 ft thick. A witness consisting of layered Celotex panels backed by a massive armor plate (shown in Figure 15) was placed approximately 4 ft from the back of the bins, and the test was covered by high-speed videography.

The last frame from the high-speed video record is shown in Figure 16. The barricade has not yet moved. The radiating lines may represent fragment trajectories. The conditions at the end of the test are shown in Figure 17. The barricade was pushed back against the witness and crushed. No fragments penetrated this barricade and entered the witness.

6. Crushing Propagation

Two computational approaches using the CTH hydrocode for assessing crushing propagation were pursued. In the first of these, the motion that may be imparted to candidate barricades by the explosion of a representative ammunition stack and the resultant loading on potential acceptors was determined. In the second, the interior loading and deformation of individual munitions under conditions known from experiment to be at the threshold of reaction were determined.

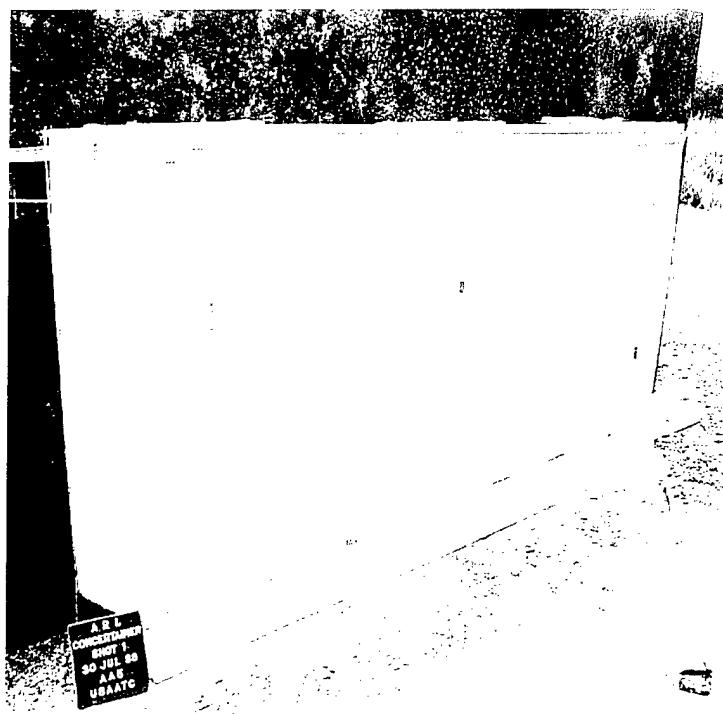


Figure 15. Celotex witness.

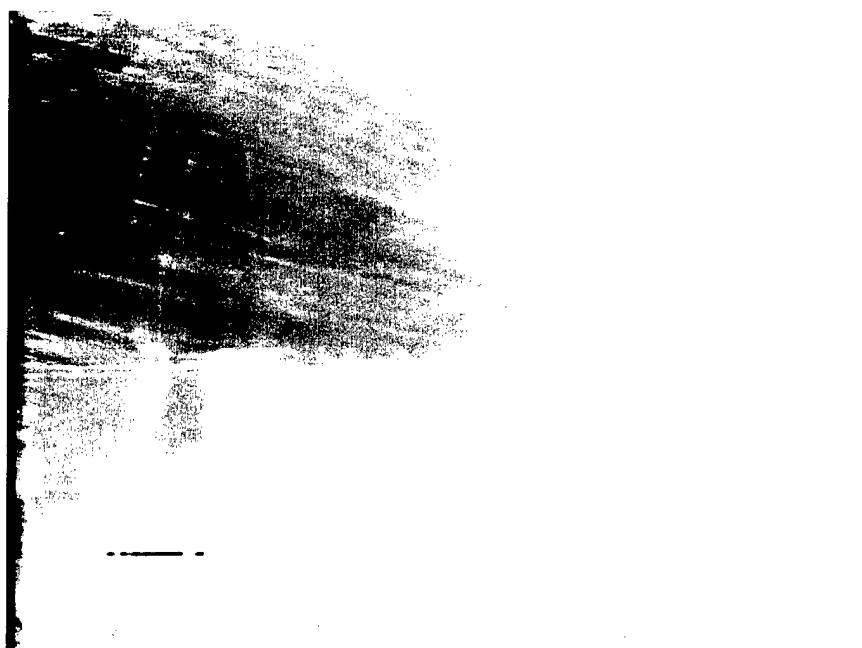


Figure 16. Video frame of early portion of the Concertainer barricade test.



Figure 17. Aftermath of Concertainer barricade test.

Two-dimensional computations of barricade response to blast loading have been conducted as illustrated in Figure 18. Lottero (1998, 1999a, 1999b, 1999c, 2000) documents two-dimensional numerical simulations of the detonation of a simplified donor stack in a temporary storage area and the subsequent effects on adjacent water barricades and a simplified acceptor stack as a function of the standoff distance between the donor and the barricade. The donor stack is represented as an uncased, condensed, high-explosive charge with a rectangular cross section. The water barricades have either rectangular or trapezoidal cross sections, and the acceptor stack is a solid rectangle. Originally, separate uncoupled computations were run to simulate the acceleration of the water barricade and its subsequent interaction with the acceptor stack. More recently, both phenomena were simulated in the same computation. The two-dimensional results indicate that initiation caused by impact of the barricade on the acceptor stack cannot be ruled out. Follow-on work modeling the phenomena in three dimensions is currently underway.

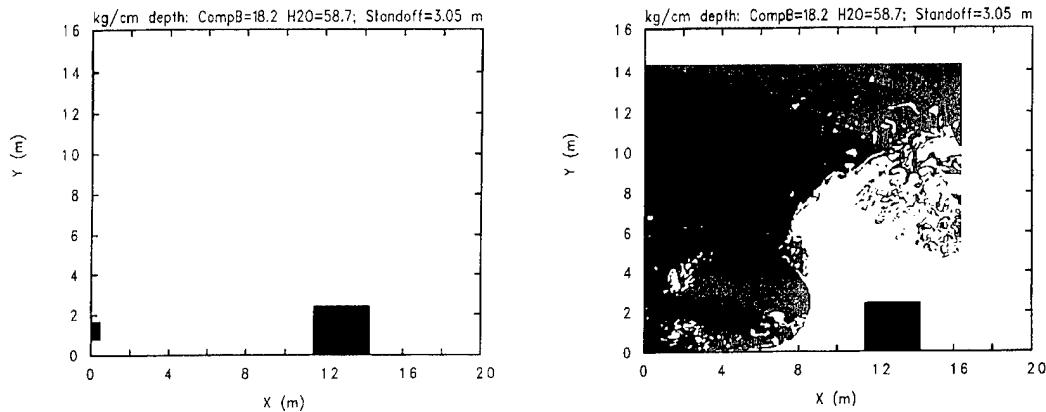


Figure 18. Materials plots at early and late times from a two-dimensional simulation of barricade and acceptor stack response to donor stack detonation.

Another series of two-dimensional CTH computations that model a steel flyer plate striking a single munition, (either an M2A3 or and M483) has been performed (Lottero and Simmers 2000, Simmers and Lottero 2000). Some of these computations simulate earlier experiments performed for the purpose of determining a worst-case acceptor for use in subsequent testing programs (Lyman et al. 1994). Two different tests were conducted. One was designed to produce an initial impact shock followed by a secondary impact shock (illustrated in Figure 19), and the other was designed to produce crushing without significant shock loading. The primary purpose of the computations is to compute the pressures that may have occurred in the explosive fill to help explain the various exothermic reactions, or lack thereof, that occurred in the experiments. In general, the computed pressures are lower than the minimum values believed to be necessary to initiate a reaction by shock

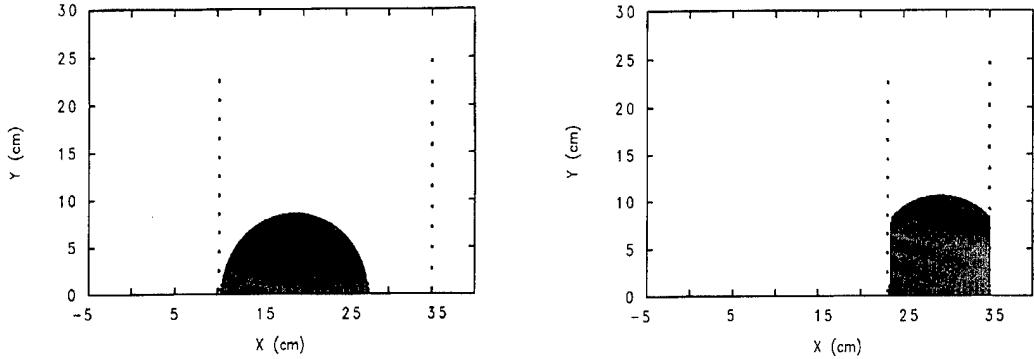


Figure 19. Simulation of munition crushing.

initiation. For shear initiation, the combined shear and shock pressures for a simulation of an experiment that produced a detonation were close to values proposed by Liddiard and Forbes (1987).

7. Fire Propagation

7.1 Wood Ignition

Vande Kieft and Hillstrom (1997) undertook a survey of information pertinent to the ignition of wood packaging by hot fragments. They concluded that fragments from exploding ordnance frequently possess sufficient energy to ignite wood and support continued combustion.

7.2 Firebrand Characterization

A series of tests was conducted in an attempt to characterize the material ejected from burning ammunition stacks that represents a hazard to other stacks nearby (Hillstrom and Starkenberg 1998b, 2001; Pergantis and Mulkern 1998). Six representative ammunition items were chosen to act as firebrand donors. They are 25-mm M791 APFSDS-T projectiles, AGM-114A Hellfire missiles, 105-mm M1 HE projectiles, 155-mm M549A1 HERA projectiles, 155-mm M864 ICM projectiles, and 105-mm M416 WP-T (white phosphorus) projectiles. A view of part of the test arrangement is shown in Figure 20. The items to be tested were attached to a steel burn stand over a propane burner. The burner was ignited remotely, and the gas flow was stopped after 30 min (earlier if the donor ordnance was expended). Distributed firebrands were “witnessed” by matrices of panels arranged along four radials extending to 200 ft from the burner. One of the radials is visible behind the ammunition in Figure 20. The panels consisted of either plywood sheets or sheet-metal trays filled with layers of JA-2 gun propellant as shown in Figure 21. In

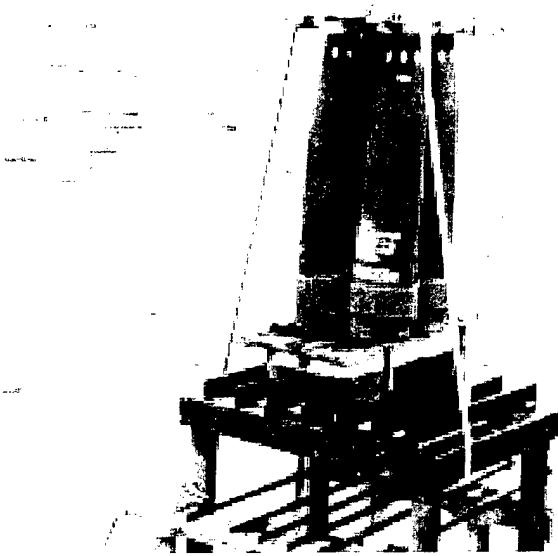


Figure 20. 155-mm M864 ICM projectiles on the burner stand with witness matrices in the background.



Figure 21. Propellant panel from a witness matrix.

addition, some of the debris fields were mapped after the tests, and some of the tests were covered by infrared (IR) videography.

A view of one of the radials after a test is shown in Figure 22. The firebrands and debris ejected in these tests varied widely. Their masses ranged from microscopic to 46 kg. Some firebrands resulting from detonations or violent explosions were launched with high kinetic energy, while others were launched more softly. The materials that were ejected included burning propellant, burning wood, molten aluminum, and unexploded submunitions. Burning of the plywood and propellant witness panels indicates that many of these ejecta could easily ignite nearby ammunition, although the cause of specific panel ignitions was often unclear. Burning propellant grains seemed to have the greatest incendivity. Burning wood also started fires easily, and molten aluminum splatters were suspected to have started several propellant tray burns. These materials tend to cool during flight and did not start fires in the propellant witness panels far from the burner. Secondary explosions of the M864 submunitions and one M549 projectile were observed downrange.

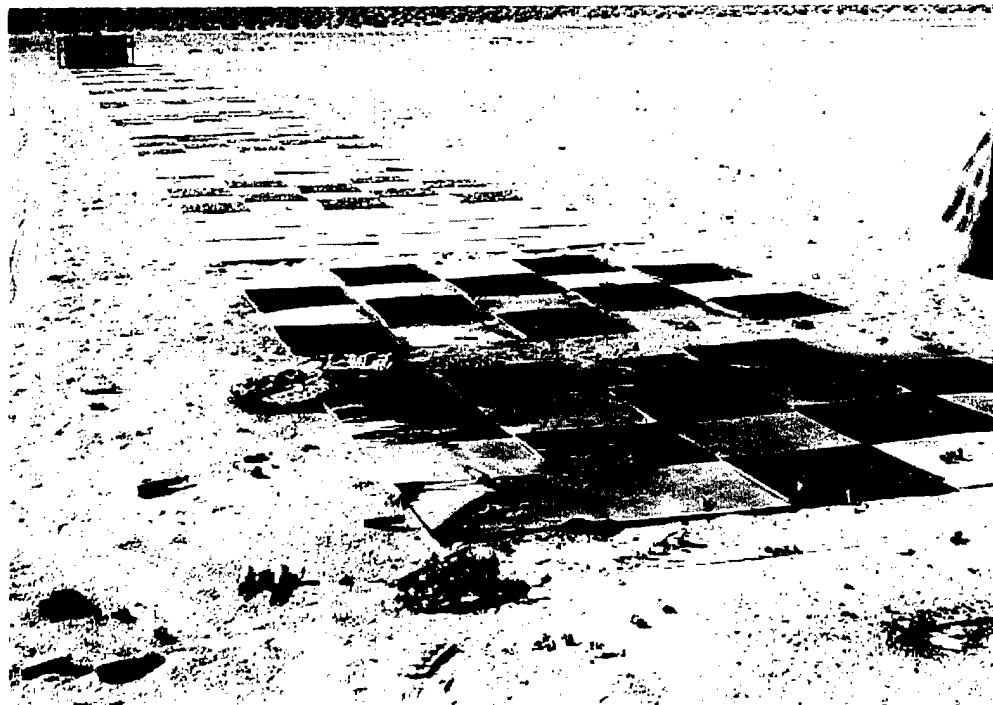


Figure 22. Radial of witness matrices after a test showing debris and scorching.

7.3 Blanket Development

In order to develop an experimental flame- and penetration-resistant blanket to protect munitions from firebrands, preliminary ballistic testing was conducted at ARL (Boyle et al. 1999). Final designs, consisting of aramid and ceramic fibers, were

subjected to several rigorous tests both in the laboratory and in the field (Mulkern et al. 2000; Chin et al. 2000). Ballistic performance was tested by firing fragments representative of falling debris at the blanket using a modified Remington 700 rifle shown in Figure 23. The blanket was found to offer penetration protection from 300- and 454-g fragments traveling at velocities of 140 and 60 m/s, respectively. It also provided flame protection from high temperature gas jets and burning JA2 and M30 propellant (with temperatures exceeding 2000 °C) for 10 s. The configuration tested and the results of one of the tests are shown in Figure 24.

8. Demonstration Testing

The demonstration tests, in which requirements for prevention of fragment penetration of barricades, acceptor crushing, and ignition of fires in acceptors were to be combined to analyze and design a test site, represent the culmination of the program. Originally, two large-scale demonstration tests, one with a detonated donor stack and one with an ignited donor stack, were planned. The test with the ignited donor was eliminated in favor of the ballistic and flame blanket tests described in the foregoing section. Instead, two tests with detonated donors were conducted, one to test FFF barricades and one to test Concertainer barricades. The tests and their results are described in detail by Sullivan et al. (2000a, 2000b).

The general test arrangement is illustrated in Figure 25. The donor in each test was a centrally detonated stack of pallets of M107 155-mm projectiles filled with Composition B. It was flanked by two identical barricades under test. Identical acceptor stacks containing four different kinds of ammunition (chosen for sensitivity to crushing ignition) backed by additional pallets of 155-mm projectiles opposed the barricades.

The test arrangement for the FFF barricades is shown in Figure 26. In the test, one of the two acceptor stacks detonated, while the other's munitions survived. No fragment marks were found on any munitions of the surviving acceptor stack. High-speed film (Figure 27) shows that the initiation time was late, consistent with a crushing mechanism.

The arrangement for the Concertainer barricade test is shown in Figure 28. Consideration of fragment penetration and stability drove the design, and the resulting barricade is more massive than the FFF design. In this test, both acceptor stacks survived. As shown in Figure 29, munitions were scattered about, but there was no sign of burning or fragment marks on any of them.

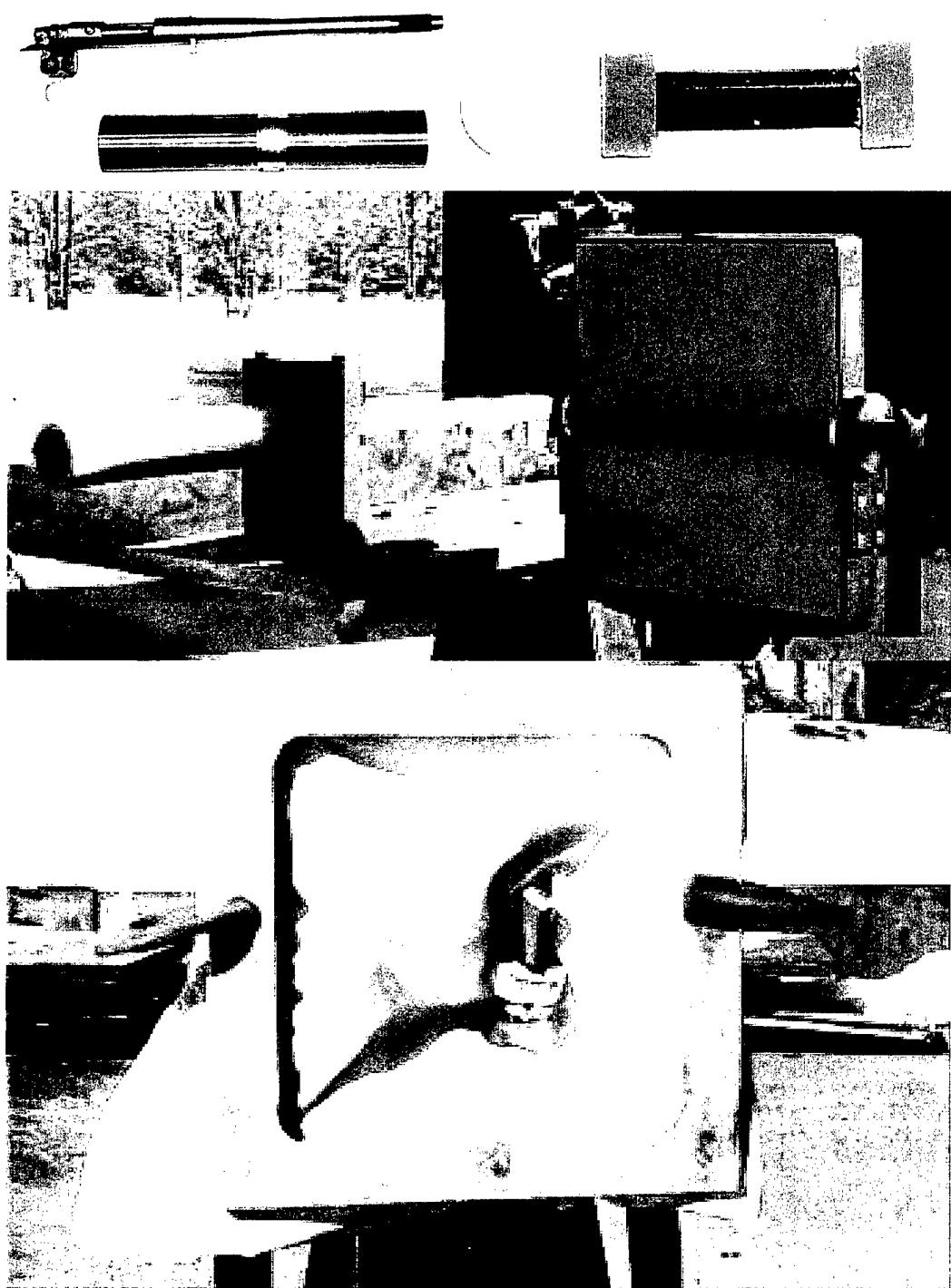


Figure 23. Modified Remington 700 rifle, 454-g steel fragment with polymer foam sabots, blanket clamped in frame after ballistic testing.

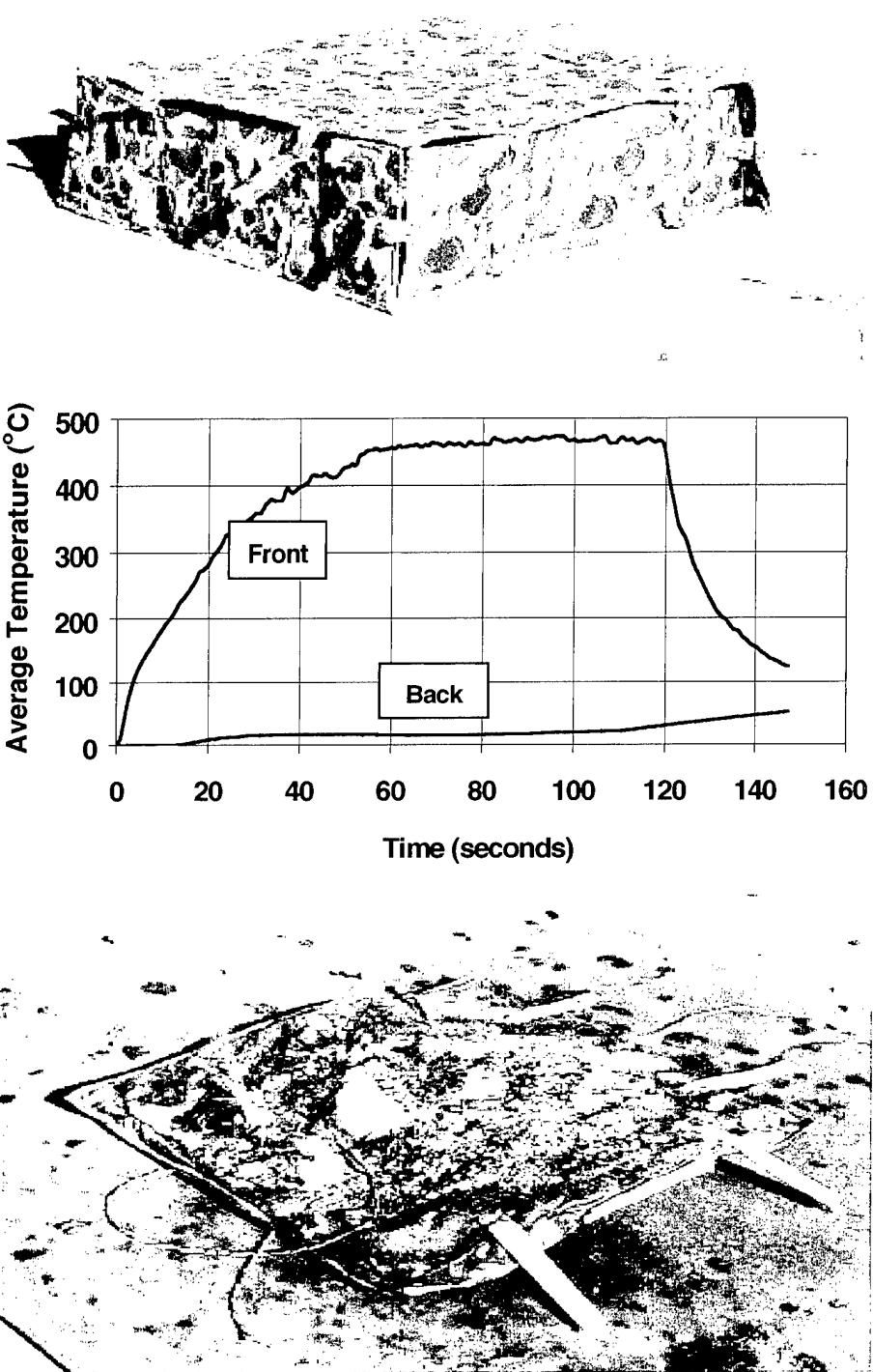


Figure 24. Blanket test configuration, typical front and back temperature records, and representative test result.

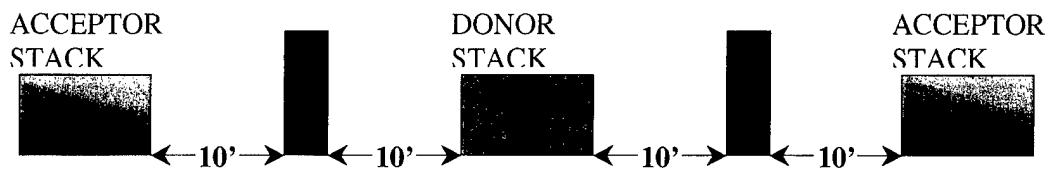


Figure 25. General arrangement for the demonstration tests.

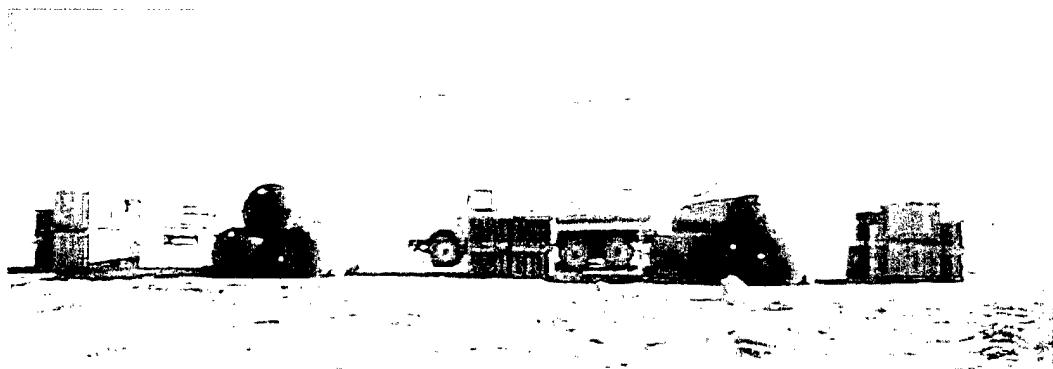


Figure 26. Arrangement for the demonstration test with FFF barricades.

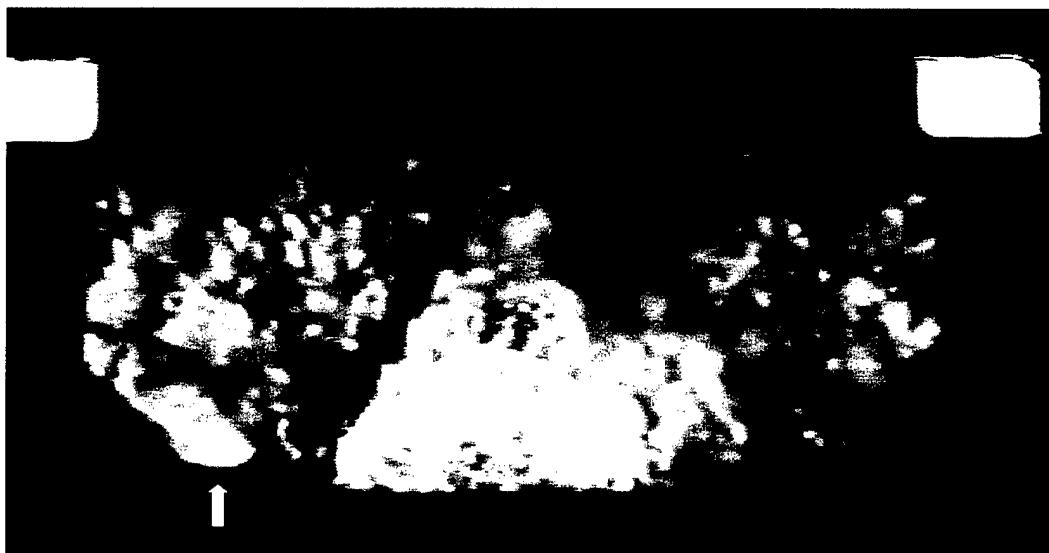


Figure 27. High-speed film frame from the demonstration test with FFF barricades showing delayed acceptor initiation at the left.

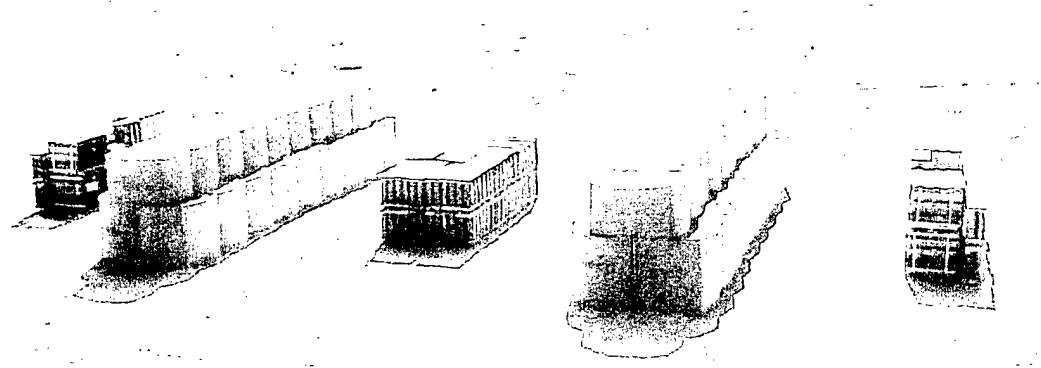


Figure 28. Arrangement for the demonstration test with Concertainer barricades.



Figure 29. Aftermath of the demonstration test with Concertainer barricades.

9. Conclusion

The results of testing the FFF water-filled barricade system show that it may not survive successive explosions occurring over long periods of time as ammunition cooks off in fires. Although dumped gel may extinguish some fires, the efficacy of this mechanism has not been established. Further, our results indicate that water may not be the best fragment attenuator. The FFF barricade was not fully successful in demonstration testing. Fragmentation did not appear to be the cause of propagation in its presence. The sand-filled Concertainer barricade was successful. The manufacturer claims that the tubular bag system can be used with alternate fills. This approach should be explored if further development of this product is considered. The blanket system developed under this program appears very promising and represents the most successful portion of the program.

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<p>The Munitions Survivability Technology (MST) program was initiated by the U.S. Army Defense Ammunition Logistics Activity to develop a rapidly deployable system of fragment barricades combined with lightweight fire-inhibiting blankets, with guidelines for their use to prevent or reduce propagation of explosions and fire between stacks of Army munitions. In order to ensure the maximum effectiveness of such systems, the U.S. Army Research Laboratory undertook a program to elucidate relevant propagation mechanisms, enhance predictive techniques for propagation, and develop data required for the evaluation of the system to be fielded. Available resources included the FRAGPROP model for predicting propagation of detonation and burning reactions between ammunition stacks, the FRAGGEN model for predicting fragmentation of items that are not characterized in arena tests, existing data on gun propellant and rocket motor vulnerability to fragment attack, analyses and test procedures developed in conjunction with the Navy's High-Performance Magazine program, and data from hazard classification tests. The MST program was divided into three broad areas: (1) fragment propagation, (2) crushing propagation, and (3) fire propagation. Tests, simulations, and analyses were conducted in each of these areas. The program culminated in two large-scale demonstration tests.</p>			
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